Measure Bode Plots in 5 Minutes

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Abstract

A Bode plot is a graphical technique for displaying the frequency response of a system. A Bode plot consists of a pair of plots: One provides the gain of a system versus frequency, while the other provides the circuit phase versus frequency. The technique is useful for both circuit analysis and design, particularly in the design of operational amplifier (OpAmp) circuits for optimal performance.

In introductory electronics courses at our university, we have found the Digilent Analog Discovery 2 (AD2) to be a very versatile instrument for student labs. The AD2 is a USB oscilloscope, logic analyzer, and multi-function instrument that allows users to measure, visualize, generate, record, and control mixed-signal circuits. With a small kit of components, a solderless breadboard and the AD2, every student can perform take-home labs as homework problems in undergraduate level courses to enhance their understanding of complex concepts and retention through the assigned hands-on experiments.

This paper describes low-cost, simple, and remote laboratory experiments designed to increase undergraduate students' understanding and retention of basic operational amplifiers concepts, the importance of frequency domain signal analysis using Bode Plots, and the practical OpAmp performance and limitations as compared to the ideal OpAmp.

INTRODUCTION

The frequency response of a system is described by how the system responds to a sine wave voltage signal with varying frequency. Generally, a Bode Plot displays the ratio of the sine wave coming out of the system to the sine wave going in.

The complex nature of the behavior of the ratio of two sine waves is plotted as the ratio of the amplitudes coming out to going in, in dB, and the phase, in degrees, using a log frequency scale. For a linear system, the Bode plot tells everything you need to know about the behavior of the system.

A system that responds like a 1-pole (1^{st} Order) low pass filter drops off at $-20\ dB/decade$ of frequency, while a 2-pole (2^{nd} Order) low pass filter response drops off at -40 dB/decade. Both of these responses are straight lines on a log-log scale. The pole frequency is easily measured as the frequency at which the response drops off by $-3\ dB$.

An important feature of the Bode Plot response of a system is that the source impedance of the input sine wave is assumed to be $0\ \Omega$, while the receiver at the output is assumed to be an open impedance. When performing real measurements, it is important to be aware of the actual output impedance of the signal source and the input impedance of the response-measuring instrument.

In real systems, a $0\ \Omega$ output impedance and infinite impedance input resistance is never achieved. However, these values should be at least 2 orders of magnitude away from the comparable values of the device under test (DUT) to maintain no more than a 1% error.

The Digilent Analog Discovery 2 (AD2) multi-function scope [1] is the perfect tool to measure the Bode Plot response of circuits. It can generate a variable amplitude, swept sine wave signal that can be measured at the input and output of the circuit using the two channels of the scope. Built in software will automatically calculate the ratio of the amplitudes and the phase shift and display a Bode Plot response.

The output impedance of the function generator is about $0.1\ \Omega$, while the input impedance of the scope channels is $1\ M\Omega$. This instrument is suitable for measuring the Bode Plot of circuits with input impedances higher than $100\ \Omega$ and output impedances less than $10\ k\Omega$. These are important constraints to be aware of when selecting circuits to measure.

INITIAL MEASUREMENTS

Generally, with a new instrument or measurement process, it is important to measure something for which one can easily verify. This establishes confidence in the measurement tool, the process, and the results. Fundamentally, the Network Analyzer feature of the AD2 generates a sine wave at the input and uses channel 1 to measure the voltage at the input and channel 2 to measure the voltage at the output of the circuit. An example of these sine waves at $1\ kHz$, is shown in Figure 1 below.

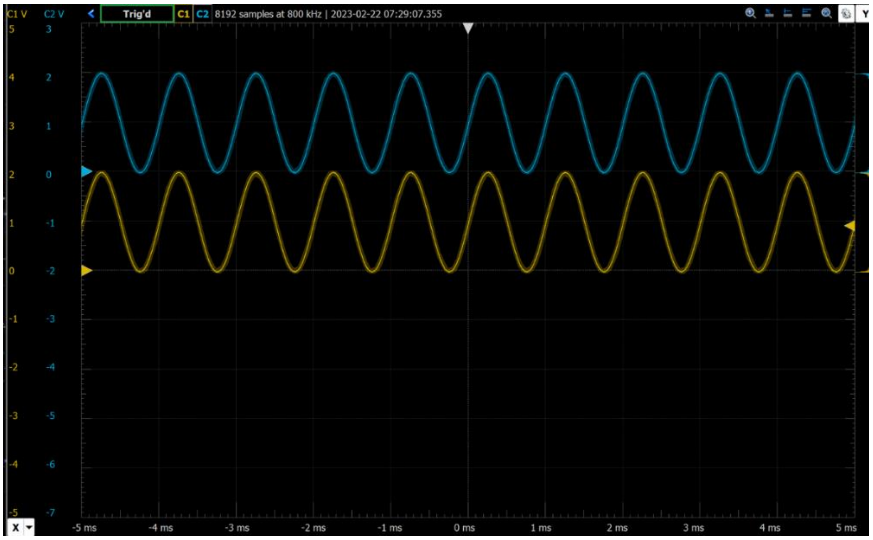

Figure 1: The sine wave signals measured at the input of the circuit and the output of the circuit.

The Bode Plot of a through connection should be a flat 0 dB response. A measured through connection is shown in Figure 2 below.

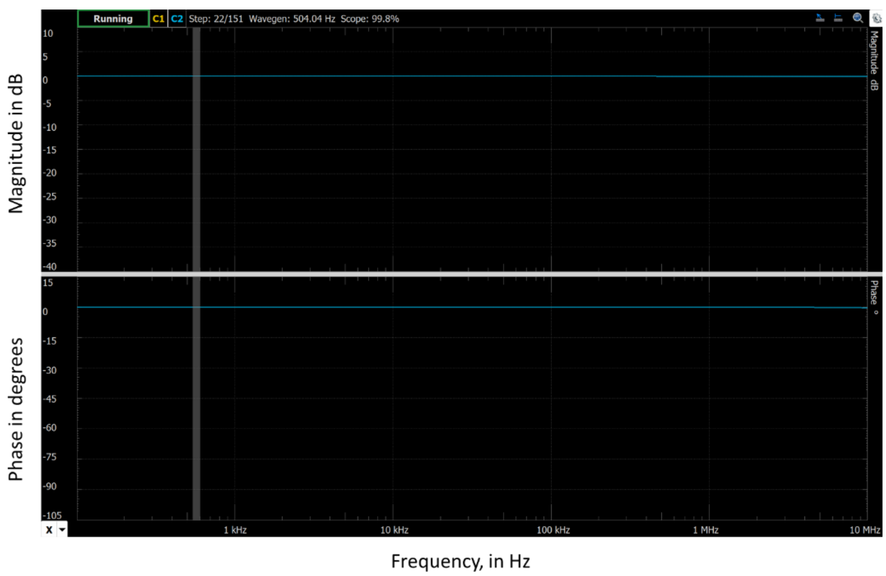

Figure 2: Bode Plot of a through connection. It has a 0 dB response and 0 degree phase shift from 100 Hz to 10 MHz

As a simple example, a low pass RC circuit was built with a 1 $k\Omega$ resistor and 0.1 μF capacitor. The cut-off frequency (f_c) is expected to be at:

$$f_c = \frac{1}{2\pi RC} = \frac{0.16}{1\ k\Omega \times 0.1\ \mu F} = 1.6\ kHz$$

The circuit and its measured Bode Plot is shown in Figure 3. The measured $-3\ dB$ cut-off frequency can be read directly off the front screen as very close to $1.6\ kHz$.

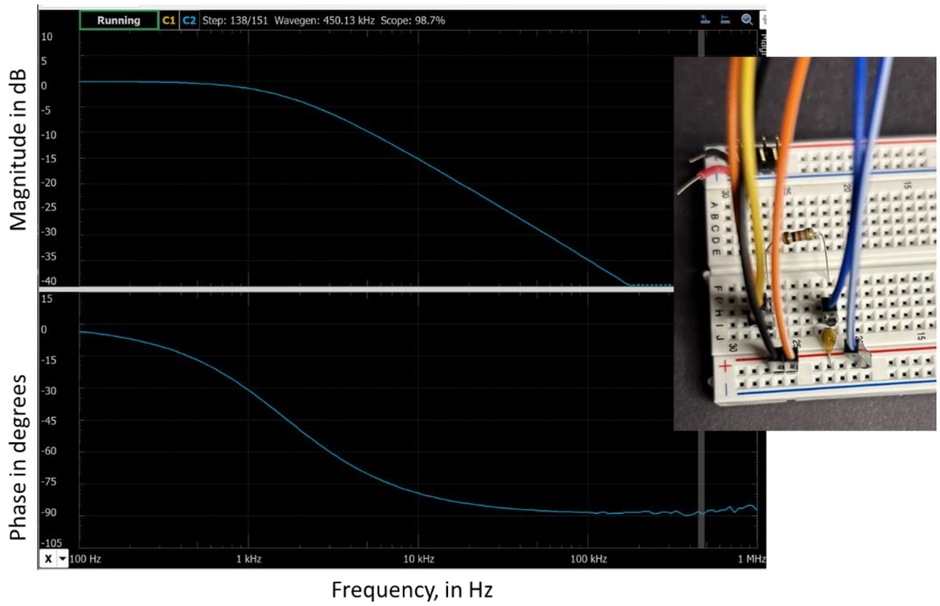

Figure 3: Measured Bode plot of a simple RC low pass filter and the actual circuit shown on the right. The phase is approximately 0 degrees at low frequency, is -45 degrees at the cut-off frequency, and is -90 degrees at high frequency can be seen.

Accurate Bode Plots of simple low and high pass filters of passive structures are easy to obtain and instructive to look at, as long as the input impedance range of greater than $100\ \Omega$ and limited output impedance range of less than $10\ k\Omega$ is followed.

OPAMP FREQUENCY RESPONSE

When operational amplifiers (OpAmps) [2]-[4] are introduced in introductory courses, they are often described as ideal amplifier circuits with infinite input impedance, gain and bandwidth. In most simple circuits, they actually behave consistent with this first order model. It is only when we look at the extremes such as higher frequency, that we can see behavior deviating from these ideal figures of merit.

The measured Bode Plot of an OpAmp reveals its finite bandwidth. The term in the spec sheet that describes its limited bandwidth is its Gain-bandwidth (GBW) product. One of the work-horse opAmps in our introductory courses and project courses is the TLV4110.

It has six features that distinguish this particular opAmp as an excellent first choice in many project applications:

- ✓ *Output impedance is* $< 1\ \Omega$
- ✓ *It can source and sink* $> 500\ mA$
- ✓ *It is single rail, capable of* $2.5\ V$ *to* $6\ V$ *operation*
- ✓ *Its output is rail to rail*
- ✓ *Input bias current is typically* $< 1\ pA$
- ✓ *Has a built-in enable pin so its output can be controlled with a digital signal*

As with many low-cost, general purpose OpAmps, this one has a slew rate of about $1.6\ V/\mu sec$ with a rated GBW product of $2.7\ MHz$. These specs are a little confusing and sometimes contradictory.

With a slew rate this large, the actual bandwidth of the response of the OpAmp will depend on the amplitude of the signal. After all, if the peak-to-peak sine wave voltage were $2\ V$, for example, it would take a minimum of $2\ V/1.6\ V/\mu sec = 1.25\ \mu sec$ just to reach the full amplitude in half a cycle. This would make the bandwidth for a $2\ V$ peak-to-peak signal less than $1/2.5\ \mu sec$ or $400\ kHz$, not the specified $2.7\ MHz$.

In fact, due to the finite slew rate of the output signal, we expect the GBW to be signal-amplitude dependent. This sort of behavior is easily measured using the built in Bode Plot analyzer in the Digilent AD2 scope. Figure 4 shows the measured Bode plot response of a TLV4110 OpAmp configured as a follower using three different input sine wave amplitudes of $10\ mV$, $100\ mV$ and $1\ V$.

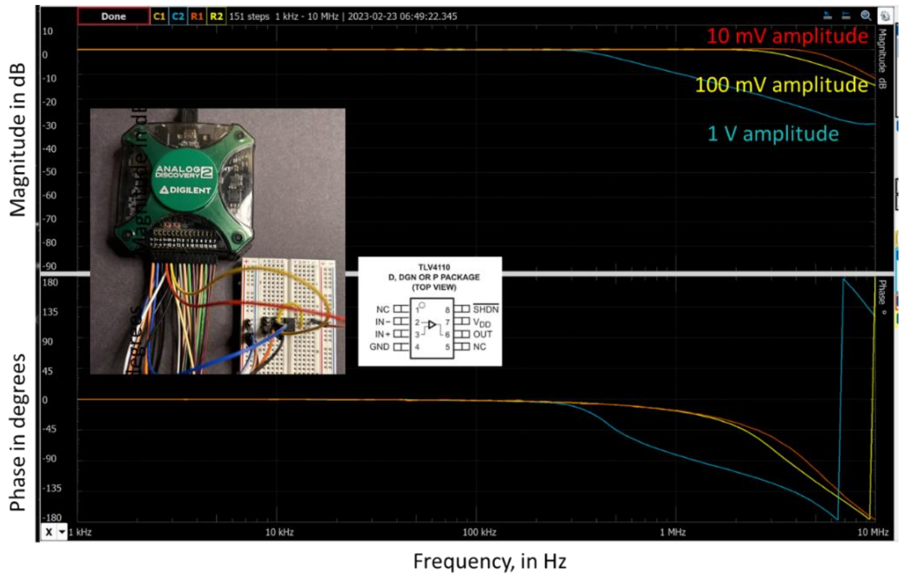

Figure 4: The Bode Plot of a TLV4110 OpAmp showing a GBW product at different input sine wave amplitudes.

In this example, the gain of the follower was unity, so the GWB product is just the $-3\ dB$ cut-off frequency. When the amplitude is small, like $10\ mV$, the measured bandwidth of the TLV4110 is $2.7\ MHz$, exactly as listed in the specification.

However, when the amplitude is increased to $100\ mV$, the bandwidth is seen to decrease slightly to $2.5\ MHz$. And, when the amplitude is $1\ V$, or a peak-to-peak value of $2\ V$, the bandwidth decreases to $500\ kHz$, very close to our rough expected bandwidth estimate of $400\ kHz$.

This just means that for large signal applications, don't expect to see the full $2.7\ MHz$ bandwidth response of this OpAmp. Given its other excellent performance figures of merit, this OpAmp is still our number one choice for many applications.

This illustrates how important it is to read datasheets, understand them carefully, and be prepared to perform your own characterization of important properties. The concept of reverse engineering critical figures of merit from measurements is an important element of all electronics courses at our university. It is reinforced using simple to use, portable kits from which take home labs can be constructed.

CONCLUSION

The Bode Plot is a fundamental characterization technique of the important properties of any electronic circuit or system. It is easily measured using the Digilent AD2 multi-function scope. Because it is so easy to use, it can be implemented in hands-on take-home labs for undergraduate electrical engineering courses to enhance students' learning and retention [5]-[13]. The lower barrier to entry for these measurements using the AD2 means that the Bode Plot can become a common place characterization tool for all circuits that students construct. This teaches the important lesson of thinking in the frequency domain.

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